Surface Preparation of Naval Ship Construction Steel (ABS-A and AH-36) via Bristle Blasting Process

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Recommended Citation
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SURFACE PREPARATION OF NAVAL SHIP CONSTRUCTION STEEL
(ABS-A AND AH-36) VIA BRISTLE BLASTING PROCESS

by:

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A Thesis submitted to the Faculty of Graduate School,
Marquette University,
in Partial Fulfillment of the Requirements for
the Degree of Master of Science

Milwaukee, Wisconsin

August 2011
ABSTRACT
SURFACE PREPARATION OF NAVAL SHIP CONSTRUCTION STEEL
(ABS-A AND AH-36) VIA BRISTLE BLASTING PROCESS

Jorge Andrés Martinez

Marquette University, 2011

Bristle blasting is a new and unique corrosion-removal process that is rapidly gaining widespread acceptance among engineers and practitioners in the corrosion/surface preparation community. Engineers from the ship construction and repair industries face a constant erosive threat to ships’ steel infrastructure and welded joints. To this end, great care is exercised in protecting the vessels’ structural integrity and longevity, while maintenance engineers in the ship-building industry seek new methods to improve surface preparation that will not compromise the surface cleanliness and anchor profile required for proper adhesion of paints and coatings.

In this study, the cleanliness and texture of surfaces generated by the bristle blasting process are examined and reported. Specifically, the present work is aimed at evaluating the cleanliness, surface profile, and material removal performance that can be achieved for steels (ABS-A and AH-36) that are commonly used in ship-building industries. In addition, the bristle-blasting process’ ability to clean and prepare welded joints fabricated from both ABS-A and AH-36 steel is evaluated as well. The experiments carried out in this study also assess the relationship between tool longevity and surface texture performance, which can form a basis for estimating the overall life expectancy of the bristle-blasting tool.

The results of the surface generated by the bristle-blasting process is compared to that generated by other conventional surface-finishing tools. A direct comparison with visual standards that are commonly used for training and certification purposes is carried out, hence, ensuring the proper characterization of the bristle blasting process in the ship construction and repair industry.
ACKNOWLEDGMENTS

Jorge Andrés Martinez

Hard work, dedication and a positive mind are not enough to succeed in your life's journey. Encouragement, advice and love are traits that only those close to you can provide, and an essential ingredient to your life.

I would like to dedicate this work my sister Maria Lucia, who has been there for me throughout this entire journey, and to my parents, Jorge and Lucia, that although vast distances separate us, whose love and encouragement has been closer than ever.

An exceptional thank you and great recognition is due to Dr. Robert Stango, for his guidance, words of wisdom and the great opportunity to work beside him on this project. I would also like to thank Monti Werkzeuge GMBH (Bonn, Germany) for their financial support and sponsorship of this project. I am very grateful as well, for the insights and teachings Dr. Raymond Fournelle and Dr. Vikram Cariapa provided throughout this project.

Finally, I would like to thank all my friends and colleagues for their unconditional support, love and words of encouragement, which made my graduate studies journey an epic adventure!

With much love, Jota.
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<td>$m_p$</td>
<td>mass of a particle</td>
</tr>
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<td>$V_p$</td>
<td>pre-impact speed of particle</td>
</tr>
<tr>
<td>$S$</td>
<td>target surface</td>
</tr>
<tr>
<td>RPM</td>
<td>revolutions per minute</td>
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<tr>
<td>$e_p$</td>
<td>working kinetic energy of a particle</td>
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<tr>
<td>$a$</td>
<td>entry angle of particle</td>
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<tr>
<td>$n$</td>
<td>speed of the hub in rpm</td>
</tr>
<tr>
<td>$m_b$</td>
<td>mass of a bristle</td>
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<td>$A_2$</td>
<td>constant introduced in Equation 2.1</td>
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<td>$L$</td>
<td>nominal bristle length</td>
</tr>
<tr>
<td>$K$</td>
<td>constant introduced in Equation 2</td>
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<tr>
<td>$\pi$</td>
<td>pi ($\approx 3.14$)</td>
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<tr>
<td>$r_h$</td>
<td>radius of the hub</td>
</tr>
<tr>
<td>$Q$</td>
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<tr>
<td>$\omega$</td>
<td>angular velocity (rad/s)</td>
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<td>$P$</td>
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\( v_{cm} \)  
velocity of center of mass of bristle

\( R_z \)  
(mean of) maximum height of the profile

\( \lambda_c \)  
profile filter, cut-off length

\( \mu \)  
10\(^{-6}\)

HRC, Re  
Rockwell Hardness C Scale

HRB  
Rockwell Hardness B Scale

 HV  
Vickers Hardness

gms  
grams units of mass

sec  
seconds units of time

min  
minutes units of time

gms/sec  
grams per second units of material removal rate
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1. INTRODUCTION AND BACKGROUND TO SURFACE PREPARATION OF NAVAL SHIP CONSTRUCTION STEELS (ABS-A AND AH-36) VIA BRISTLE BLASTING PROCESS

1.1. Introduction

Commercial ships are constantly exposed to harsh environmental conditions that lead to the deterioration and structural compromise of their material systems. One material system that is very susceptible to the environmental conditions that the ship is exposed to its steel infrastructure. Special paints and coatings have been developed to prevent corrosion. These paints and coatings help to not only protect the steel infrastructure, but they also prolong the life of the vessel’s steel components that would otherwise be compromised due to corrosion.

Although great advances have been made in the development of protective paints and coatings to prevent corrosion, these coatings do not posses an infinite life and ultimately degrade and experience reduced efficiency. This requires the application of a new coating layer. Before the application of the new coating layer, the deteriorated layer must be removed and the surface must be cleaned and predisposed to ensure a successful application of the new coating layer. Various mechanical surface cleaning technologies have been developed by engineers to achieve this task. These type of tools are designed to function with two goals in mind: 1) to be able to remove the corrosion product and deteriorated coating layer simultaneously and 2) to generate a course, rough surface profile commonly known in the industry as an anchor profile, generally specified by paint
and coating manufactures as an $R_z$ value above 50 microns. As mentioned before, these two criteria must be achieved before the application of protective paints and coatings.

Currently, commercial ship repair sites utilize three common methods and tools to achieve the prescribed surface finish for the application of protective paints and coatings. These three methods and tools are: grit blasting, needle guns, and wire brushes. These three methods and tools will later be discussed in greater depth. A fourth and novel tool called *Bristle Blasting* has been gaining attention in the ship repair industry after proving successful in the surface cleaning and preparation of corroded steel piping API-5L.

Due to its success, the bristle blasting process is being introduced to other repair applications that face corrosive degradation of their steel components. The commercial ship construction industry is constantly facing a corrosion removal and surface preparation challenges at their ship repair sites, making it a great candidate for the implementation of this novel tool. The main construction steels that are used in commercial shipyards are AH-36 and ABS-A. This study will evaluate the performance of the bristle blasting process on these two type of materials by quantifying the ability of the tool to remove the corrosive layer and expose substrate material. It will also evaluate the surface texture and profile the tool achieves on these material systems, since goal of the bristle blasting process is to simultaneously clean and generate an anchor profile.
Furthermore, this study will investigate the performance of the bristle blasting tool when it encounters a weld bead on its work path, due to this frequent occurrence in commercial ship design. This weld bead study will be carried on for both steels, AH-36 and ABS-A, welded surfaces.

### 1.2. Review of Traditional Processes

#### 1.2.1. Grit Blasting

Grit blasting is one of the most common and widely used processes for surface treatment. Grit blasting is described as a free-impact surface treatment that involves the use of loose abrasive grains which are propelled at a controlled and prescribed force towards a target surface. Figure 1.1 shows a schematic diagram of the abrasive blasting process, in which the abrasive grit media having a particle mass \( m_p \) leaves the nozzle at a velocity \( v_p \) and strikes the target surface \( S \). When the abrasive media impacts the target surface it forms a crater-like micro-indentation shown in Figure 1.2, which removes the corrosive layer and exposes fresh substrate material. The fresh exposed material displays an anchor profile optimal for paint and coating adhesion. The cleaning process is very efficient and ideal for treating large surface areas \(^1\).

Nevertheless, the grit blasting process has some major disadvantages that the industry must face when utilizing such cleaning method. First and foremost is the high cost of the abrasive blast system. It is a complex and involved system that requires
technical maintenance for a satisfactory performance. This leads to a significant capital investment that the industry must keep in mind. Given the size of the abrasive system, another issue that could be concerning in some applications is the portability of the equipment to the work site. This is even more concerning when working in confined spaces. Although the cleaning process is very efficient, the set-up time of the equipment and the working area is time consuming. This is due to the fact that the abrasive grit media must be recovered after the cleaning operation to prevent pollution of the environment. To conclude, the operator must wear a full protective suit to prevent harmful effects from the hazardous airborne contaminants in the environment during the cleaning process.

1.2.2. Needle Guns

The needle gun, which is shown in Figure 1.3, consists of a bundle of parallel wire rods or “chisels” that are placed in contact with the work part surface. When the tool is activated, the wires rapidly oscillate back and forth (i.e., along the axial direction), thereby causing repeated contact and indentation between the wire tips and the target surface. This repeated contact, in turn, leads to the removal of surface debris and simultaneously generates the coarsened surface texture, (see Figure 1.4); however, it does not resemble an anchor profile texture for optimum paint and coating adhesion. This is a popularly used tool in the commercial corrosion repair. However, recent studies have shown that prolonged use of heavy vibration tools, such as the needle gun, may cause vibration-induced white finger syndrome to the hands of the user.
1.2.3. Wire Brushes

Wire brushes are a very common tool used in surface cleaning. Wire brushing tools are comprised of flexible metallic bristles that are anchored to a rotating hub, as shown in Figure 1.5. As the hub rotates, wire tips repeatedly contact the work part surface and generate striations, or score markings throughout the region of contact. These striations are caused by bristle tips which essentially plow through the contact zone, thereby generating a multitude of parallel troughs that remove both surface debris and parent material. Consequently, the textured surface consists of striations/score markings depicted in Figure 1.6, which trace the path that individual bristle tips have traversed during the material removal process.

This process is less aggressive and cannot achieve the required surface profile for satisfactory coating and paint adhesion. However, extensive research in the mechanics of the wire brush interaction with the target surface, have laid the foundation for the design of bristle blasting process mechanics. Later studies have shown that with the correct bristle design, a single crater indentation can be constantly generated on the work surface. This achievement results in a surface finish resembling that obtained in the grit blasting process but generated by a rotary bristle tool.
1.3. The Bristle Blasting Process

1.3.1. Bristle Blasting Tool

The recently developed bristle blasting tool, pictured in Figure 1.7, can be powered either by an electrical or pneumatic power source. The tool has a brush-like appearance and consists of sparsely populated steel wires with sharpened tips. As the specially designed spindle rotates at approximately 2,500 rpm, each bristle tip strikes the metallic surface and immediately retracts/rebounds, thereby causing a multitude of impact craters. These craters resemble those formed during grit blasting operations. This repetitive process both removes the corrosive layer and generates a fresh surface having the coarse surface pattern shown in Figure 1.8. The tool displayed in Figure 1.7 also shows the specially design accelerator bar which increases the kinetic energy of the bristle tips prior to impact on the target surface.\(^8\)\(^-\)\(^9\).

1.3.2. Bristle Tool Design and Mechanics

As a result of careful design and a research studies carried at Monti Werkzeuge and Marquette University, a successful bristle design was developed to achieve a single impact crater on a target surface. Figure 1.9 shows three different bristle prototype designs (reverse bent knee, straight without bend, and forward bent knee) as they strike the target surface.\(^10\) Further studies were able to track the displacement of the prototypes bristle tips and plot
them on an X and Y plane to investigate their behavior as they strike the work surface. The results of these studies can be seen in Figure 1.10.

The details concerning the design of a bristle blasting tool are shown in Figure 1.11, whereby sparsely populated bristles are attached and protrude through the hub or belt, which is constructed from a flexible, high-strength, fiber-reinforced polymer that both dissipates and stores energy during the collision process. The impact dynamic properties of the tool are shown in Figure 1.12, whereby several consecutive frames acquired by a high-speed digital camera have been superimposed for a single bristle rotating in the counterclockwise direction at approximately 2,500 rpm. As the bristle tip approaches the work part surface, (motion is from left-to right) initial contact is made at the indicated point of impact. Upon striking the surface, a crater-like micro-indentation is formed and the bristle tip subsequently rebounds from the surface. Throughout this duration, the hub continues to rotate and the final trajectory of the bristle tip results in a single or primary impact site. The typical impact craters that are formed on a ductile steel surface are shown in Figure 1.13 and have been likened to shoveling craters that are commonly generated by grit blast media.

The relationship between the kinetic energy of a grit particle and a rotating bristle has been of great interest since it provides a foundation for comparing the relative performance that one may expect when using the two different processes. In research conducted by Monti Werkzeuge and Marquette University, a relationship between the
kinetic energy of a grit particle and a rotating bristle was successfully developed\textsuperscript{14}. Figure 1.1 shows a schematic representation of the grit blasting process which consists of a pressurized system that ejects media from a nozzle at speeds that typically range from 30-120 m/s. The kinetic energy of grit particle ($e_p$) is customarily computed:

$$e_p = \frac{1}{2} m_p v_p^2 \sin^2 \alpha$$

where ($v_p$) is the speed of a grit particle having mass ($m_p$), whose supply nozzle is inclined at an angle ($\alpha$) relative to the horizontal target surface\textsuperscript{15}.

The estimate for the kinetic energy of a wire bristle can be computed for a rotary tool that involves the use of an accelerator bar, as shown in Figure 1.7. This device consists of a stationary rod that is strategically placed in the path of an oncoming rotating bristle and is further illustrated in Figure 1.14. Thus, the oncoming bristle strikes the accelerator bar and subsequently retracts (Figure 1.14), thereby storing additional (potential) energy prior to being released. Upon recoil (Figure 1.15), the potential energy is converted to kinetic energy and the bristle acquires additional speed prior to impact with the target surface. Through this derivation, the research study was able to show that the relationship between the speed of a grit particle ($v_p$) and the spindle speed ($n$) (rpm) of the bristle blasting tool can be represented by the following equation:

$$v_p = \frac{1}{\sin \alpha} \sqrt{\frac{m_b}{m_p} \left\{ A_1 + A_2 \right\}}$$

Where,
Given that \( m_b \) is the mass of the bristle, \( L \) is the nominal bristle length, \( r_h \) is the radius of the bristle tool hub, and \( K = 1208.5 \). A direct comparison of equations (1) and (2) would result in the relationship between the energy equivalence that the two different processes posses. To illustrate this relationship, Figure 1.16 shows a correlation plot between the speed of the hub \( n \) (rpm) and the grit velocity \( v_p \) in (m/s). As an example, the use of G16 steel media (diameter \( \approx 1 \) mm) having a nozzle exit speed of 95 m/s corresponds to bristle blasting tool operating at the spindle speed \( n = 2,600 \) rpm.

1.3.3. Implementation of the Bristle Blasting Process

All manual surface treatment processes require dexterity, visual acuity, and a basic understanding of key parameters that affect the performance of surface finishing equipment. Training and experience are, important factors that enable users to develop skills that are needed for a successful outcome. The skill-sets that are essential for the successful application of the bristle blasting process are quite similar to those needed for other surface treatment processes. These include: 1) proper orientation of the tool in relation to the target surface, 2) control of the tool force exerted onto the surface, and 3) the feed rate and direction of the tool during operation. In the following discussion, each
of these user-based considerations is briefly discussed within the context of a common corrosion removal application.

- **Initializing the process cleaning parameters**

  Appropriate selection of the bristle blasting process parameters can be readily established by first identifying a candidate surface that requires cleaning and isolating a portion of the surface for initial cleaning/testing. In general, the face of the tool hub is oriented perpendicular to the treated surface during use, as shown in Figure 1.17. During corrosion removal, the bristle tips are brought into direct contact with the corroded surface using minimal applied force and the rotating tool is gradually moved along the feed direction to the left or right of the user (see Figure 1.17a). Thus, the appropriate pressure and feed rate of the tool is obtained by direct experimentation and the visual inspection of the trial-tested region to ensure that the desired cleaning standard or requirement is reached.

- **Method/pattern for continuous systematic cleaning**

  Having obtained the appropriate process parameters for corrosion removal, the user then identifies the region to be treated and develops a simple plan for obtaining complete coverage. As shown in Figure 1.17a, for example, the surface of a corroded steel component must be cleaned. The user has elected to begin the corrosion removal process at the extreme left end of the component and has applied the working surface of the tool along the feed direction, i.e., from left to right. This procedure has resulted in a
cleaned and textured horizontal band or row, which is shown in Figure 1.17a. Equally important, the user has started the cleaning operation along the top (uppermost) portion of the corroded surface and will perform all subsequent cleaning by the use of overlapping bands that have their starting point below (under) the previously cleaned region. That is, correct use and optimal cleaning/texturing performance of the tool requires that each overlapping successive band is generated beneath the previously cleaned region/row. Therefore, as shown in Figure 1.17b, the user has correctly overlapped the previously cleaned region and has generated/cleaned the next row by placing the working surface of the rotating tool directly below the initially prepared surface.

- Completing the corrosion removal process

Corroded components can be completely cleaned by repeating the previously described procedure. Thus, as shown in Figure 1.17c, the top surface of the corroded beam has been completely cleaned and the user is ready to remove corrosion from any remaining surfaces. Finally, if any portion of the surface is identified where unsatisfactory cleaning has occurred, the user can return to these locations for final “touch-up” cleaning as needed 17.

1.3.4. Bristle Blasting Successful Applications

Since the release of the bristle blasting process, surface treatment engineers and scholars have started to question the success of the bristle blasting process in their respective applications fields. In 2009 Neil Wilds researched the bristle blasting process
as a surface preparation method for on and off shore structures that are subjected to corrosive environments. In his study, Wilds evaluates the resulting surface texture profile and coating adhesion strength from a bristle blasted surface. Wilds also compares these metrics to other two commonly used processes: power disc tool and grit blasting. A summary of the surface profile results from Wilds' study are presented in Table 1.1 and 1.2. Where $R_{\text{max}}$ is the largest peak to valley measurement in the sampling length and $R_{\text{pc}}$ is the number of peak/valley pairs per unit length. From these results Wilds concludes that the bristle blasting process performs better than the power disc tool and the data recorded shows that the bristle blasting process was on par with the results obtain by the grit blasting method.

Table 1.1: Profile Measurements on Rust Grade A (Ref. 18).

<table>
<thead>
<tr>
<th>Surface Preparation Method</th>
<th>$R_{\text{max}}$ Range (mils)</th>
<th>$R_{\text{pc}}$ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bristle Blasting</td>
<td>2.4 - 4.6</td>
<td>23 - 35</td>
</tr>
<tr>
<td>Power Tool Discing</td>
<td>1.0 - 1.8</td>
<td>38 - 78</td>
</tr>
<tr>
<td>Grit Blasting</td>
<td>2.9 - 3.4</td>
<td>45 - 51</td>
</tr>
</tbody>
</table>

Table 1.2: Profile Measurements on Rust Grade D (Ref. 18).

<table>
<thead>
<tr>
<th>Surface Preparation Method</th>
<th>$R_{\text{max}}$ Range (mils)</th>
<th>$R_{\text{pc}}$ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bristle Blasting</td>
<td>2.7 - 4.3</td>
<td>14 - 30</td>
</tr>
<tr>
<td>Power Tool Discing</td>
<td>1.9 - 3.2</td>
<td>8 - 17</td>
</tr>
<tr>
<td>Grit Blasting</td>
<td>3.5 - 4.9</td>
<td>37 - 50</td>
</tr>
</tbody>
</table>
The results for the coating adhesion strength are reported in Figure 1.18. For this metric Wilds concurs that the bristle blasting process performed well compared to the other two studied methods. One important remark made by the present study is that the bristle blasting process is a great choice for small repair surface challenges, due to its easy equipment set-up and use 18.

In another important research study, by Dr. Robert J. Stango and Piyush Khullar explored the performance of the bristle blasting process on API-5L steel, a common pipe material in the petroleum industry. The bristle blasting process was subjected to two main parameters to measure its performance against API-5L. The two parameters measured in the study were the material removal capability of the process and the surface texture roughness that was achieved with the tool on the material in question. Throughout these experiments, the authors also were able to assess the tools life expectancy and compared it with its performance.

The material removal studies were of great interest as it showed the capability of the tool to remove the rust layer as well as some amount of substrate parent material. Figures 1.19 and 1.20 show a portion of the results collected during the material removal experiments. From these results, two observations of the tool behavior were clear. One, observation showed that at greater penetration depths, the amount of material being removed was greater. In the second observation it was clear how the material removal
capability of the tool diminished with time of tool use. These observations mentioned above can be seen in Figures 1.19 and 1.20.

To characterize the surface texture performance of the bristle blasting process, the authors used a measurement of the average peak-to-valley depth, a parameter referred as the $R_z$ value. This parameter is often used to measure the ‘anchor-profile’ of a clean surface prior to the application of any paint or protective coating. Figure 1.21 shows the results of a cleaning experiment of heavily corroded API-5L. $R_z$ measurements were taken every 10 minutes throughout the tool’s duty cycle. It is clear that the surface roughness profile decreases as the tool use time increases and after about an hour of service the surface roughness reaches its lowest acceptable limit.

The conclusion the study shows a direct cleanliness comparison between a surface treated with the bristle blasting process and those published by the Society for Protective Coatings (SSPC). The bristle blasting process exceeded the published standards. The bristle blasting process outclasses the cleanliness that is achievable with any power tool cleaning process, including power brushes, sanding discs, and needle guns. With the results presented in this study, it is clear that the bristle blasting process is a great candidate for the corrosion removal and as a surface treatment method for the petroleum pipe steel API-5L.
1.3.5. Bristle Blasting Process Qualities and Advantages

From the previously mentioned research studies and the described characteristics of the bristle blasting process, it appears that this surface treatment method mimics the crater formation and anchor profile given by the grit blasting process. However, the bristle blasting process offers some advantages that the grit blasting lacks, such as the low cost of the process. The bristle blasting system is maintenance free with inexpensive tool replacement cost. It is a highly portable system and has a very simple plug-and-play set-up operation. The method is very eco-friendly, since there is no forced recovery of hazardous by products. This allows the operators to wear minimal protective equipment, increases their comfort level, and allows for reduced fatigue for a more efficient workflow.
Figure 1.1: Schematic of abrasive blasting process (Ref. 1).

Figure 1.2: Characteristic grit blast surface generated by G16 steel media (Ref. 1).
Figure 1.3: 12-rod pneumatic needle gun (Ref. 1).

Figure 1.4: Typical texture surface after corrosion removal via needle gun (Ref. 1).
Figure 1.5: A conventional wire brush (Ref. 1).

Figure 1.6: Typical brushed surface illustrating continuous score markings generated throughout the contact zone (Ref. 1).
Figure 1.7: Recently developed bristle blasting power tool system (pneumatic version shown) (Ref. 1).

Figure 1.8: Characteristic surface generated by bristle blasting process (Ref. 1).
Figure 1.9: Three different bristle design prototypes. Reverse bent knee (left) straight without bend (center) and forward bent knee (right) (Ref. 2).

Figure 1.10: Tip displacement tracking of three different bristle designs (Ref. 2).
Figure 1.11: Design and construction of the bristle blasting tool (Ref. 1).

Figure 1.12: High speed photography of a single bristle, approaching (frames 1, 2, and 3), impact surface (frame 4), retraction (frame 5), and return to equilibrium position (frames 6-11) (Ref. 13).
Figure 1.13: Typical impact craters generated by bristle blasting tool (material system: API 5L) (Ref. 13).

Figure 1.14: Bristle tips initial contact with the accelerator bar and subsequent rear-ward retraction (Ref. 14).
Figure 1.15: Acceleration of bristle tip towards the target surface upon release from the accelerator bar (Ref. 14).

Figure 1.16: Relationship between spindle speed and grit velocity for various steel media. (Note: spindle speed 2600 rpm corresponds to grit velocity of 95 m/s for G16 media, and wire bristle having the following dimensional data: face width: 22 mm, hub radius: 27.5 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480) (Ref. 14).
Figure 1.17: Recommended use of bristle blasting tool for corrosion removal. First, a horizontal row is prepared (Fig. 1.17(a)) using minimal applied force and steady feed rate. The process is then repeated by overlapping the second row (Fig. 1.17(b)) with the previous row that was cleaned. Finally, the entire surface is cleaned (Fig. 1.17(c)) by repeatedly overlapping each row with the previously cleaned region until full coverage is completed (Ref. 1).

Figure 1.18: Average adhesion values for three methods tested (Ref. 18).
Figure 1.19: Material removal data, on API-5L steel, from a 25 minutes old tool at three different penetration depths (Ref. 19).

Figure 1.20: Material removal data, on API-5L steel, at a depth of 4mm for three different tool ages (Ref. 19).
Figure 1.21: Surface texture values, $R_z$, on API-5L steel as a function of the tools life (Ref. 19).
2. PROBLEM STATEMENT

2.1. Research Void

Given the previous success of the bristle blasting process, described in the previous section, engineers from industries that face corrosion removal challenges have began to explore the implementation of this process to their needs.

Engineers from the ship construction and repair industry face a constant corrosive threat to a ship’s steel infrastructure. It is of great importance to keep a ship’s infrastructure corrosion free, since this phenomena could lead to structural damage and compromise the operation of the vessel. A particular challenge this industry faces currently during the corrosion removal process is the confined and challenging geometrical spaces the operators must reach to properly remove corrosion affected areas. Many of the tools currently used by this industry have a hard time reaching corrosion affected spots, or the set-up and implementation of the cleaning method is complex and time consuming. A new tool and process with the qualities, such as the ones offered by the bristle blasting process, could offer many advantages to the ship building and repair industry.

2.1.1. Bristle Blasting Tool Performance on Commercial Ship Steels

The main construction steels that are used in the Naval shipyards are steel AH-36 and ABS-A. This study is concerned with evaluating the performance of the bristle
blasting process on these two types of structural steels. To do so, the bristle blasting process will be evaluated with in three categories: 1) material removal, to evaluate the corrosion removal performance and the exposure of parent material, 2) surface profile and roughness, to evaluate the ability of the tool to created an anchor profile, which is very important for the correct adhesion of paints and protective coatings, 3) surface cleanliness and texture, to evaluate the cleanliness condition of the material system after undergoing the bristle blasting process. The success on each of these three categories will determine if the process is adequate to be implemented on the material systems in question.

2.1.2. Bristle Blasting Tool Performance on Welded Joints in Commercial Ship Steels

In order to fully protect the marine vessels structural integrity great care is exercised in producing and protecting welded joints because the integrity of these seams provides a cornerstone for ensuring their structural longevity. At the same time, maintenance engineers in the ship building industry are faced with the continual need for deploying new methods for surface preparation that will not compromise the surface cleanliness and anchor profile requirements that are necessary for proper adhesion of paints and coatings.

The second part of this study focuses on the application of the bristle blasting process for cleaning and preparing welded joints fabricated in both ABS-A and AH-36
steels, which are commonly used in the commercial ship building industry. To assess the
success of applying the bristle blasting process on welded seams three categories will be
evaluated: 1) material removal, to evaluate the corrosion removal performance and the
exposure of parent weld material, 2) surface profile and roughness, to evaluate the ability
of the tool to created an anchor profile, which is very important for the correct adhesion
of paints and protective coatings, 3) surface cleanliness and texture, to evaluate the
cleanliness condition of the welded seam after undergoing the bristle blasting process.
The success on each of these three categories will determine if the process is adequate to
be implemented on welded seams of steels ABS-A and AH-36.
3. BRISTLE BLASTING TOOL PERFORMANCE ON COMMERCIAL SHIP CONSTRUCTION STEELS

3.1. Commercial Ship Construction Steels AH-36 and ABS-A

The material systems that this study focuses on are the commercial ship steels AH-36 and ABS-A. Both of these structural steels belong to the standardized American Bureau of Shipping (ABS) and are used for shipbuilding. ABS steels are divided into ordinary-strength and higher-strength grades. However, all ABS steels have been designed and composed for longterm application, which is a key factor in the shipbuilding industry.

3.1.1. Ordinary-Strength ABS-A Steel

The ordinary strength steels are divided into a number of different grades, A, B, D, E, DS, and CS. The various grades vary in the alloy composition and fracture toughness. As mentioned before, one of the material systems that this study is based on is steel ABS-A. This particular steel exhibits a minimum yield strength of 34 ksi and a tensile strength of 58-71 ksi. Steel ABS-A average a Vickers hardness of 156 (see Table A.2), this measurement was taken in the laboratory. A chemical composition table for steel ABS-A can be found in the Appendix (Figure A.1). Photographs of the microstructure of steel ABS-A can be view in Figures 3.37 and 3.38. The microscopy reveals a typical hot rolled carbon steel, with a fair amount of perlite and course ferrite grain structure.
3.1.2. High-Strength AH-36 Steel

High-strength ABS steels are available in six different grades of two strengths. These steels grades are: AH-32, DH-32, EH-32, AH-36 DH-36 and EH-36. The ‘32’ grade steels have a yield strength of 45.5 ksi and a tensile strength of 64-85 ksi. The ‘36’ grade steels have a higher yield strength of 51 ksi and a tensile strength 71-90 ksi. AH-36 average a Vickers hardness of 183 (see Table A.3), this measurement was taken in the laboratory. To assess the performance of the bristle blasting tool on a high-strength ABS steels, the material chosen in the study is steel AH-36. A chemical composition table for steel AH-36 can be found in the Appendix (Figure A.2). Photographs of the microstructure of steel AH-36 can be view in Figures 3.39 and 3.40. The microscopy reveals a typical hot rolled low carbon content steel. The microstructure shows fairy low amounts of perlite and a finer ferrite grain size structure, thus giving AH-36 the high mechanical strength properties mentioned above. The chemical composition of steel AH-36 shows traces of Columbium and Vanadium, whose presence contributes to the high hardness characteristics of steel AH-36.


3.2.1. Introduction to Material Removal Studies

The process of removing corroded layers through a mechanical method is accompanied by the removal of base or parent material as well. Material removal is an important metric in assessing the performance of the bristle blasting tool on a specific
material system. This is done by quantifying the amount of material removed at a specific penetration depth and during a set amount of time. This is an important metric because it not only demonstrates the ability of the tool to remove the corrosive layer and expose fresh substrate material but also quantifies the performance of the tool as it ages, since the experiment is performed using bristle blasting tools with different service time intervals of use.

### 3.2.2. Experimental Set-Up and Procedure for Material Removal Studies

The material removal studies were carried out by using a 3-axis milling machine, with a resolution of +/- 0.001” in all three directions. Penetrating the rotating tool into a machined ground surface of the material system in question (ABS-A or AH-36) at a specific and predetermined penetration depth. Penetration depth is defined as the measured displacement or insertion of the tool into the target surface from the initial point of contact of the bristles during rotation. Hence, the tool was allowed to extract parent material for a pre-defined and precise time interval with no interruption. The precise working time period on the specimen was achieved by using a servo motor to move the milling table in the tool working direction. Previous to activating the servo motor, to move the table, the desire penetration depth was set on “dummy” coupons that flank both sides of the specimen. The “dummy” coupons eliminate any inaccuracy that an “edge effect” could cause as the tool works on the specimen. In this manner the material specimen was subject to a constant and precise working time interval and penetration depth. Figure 3.1 shows the experimental set-up described above for the material removal
studies. After each time interval the specimen was weighed using a high resolution electronic balance, and the difference in weight (equivalent to the material removed) was recorded.

In order to establish the effect that tool wear or tool life has on the material removal process, three different tools were used, each with a different amount of continuous use or different “age”. The prescribed tool “ages” used throughout the study are “new” tool (i.e., as-received), 25 minute tool and a 60 minute tool. These times of continuous used were chosen as the average bristle blasting tool life is approximately 60 minutes as they have been implemented in previous research studies.

Another important variable during the implementation of the bristle blasting process is the penetration depth of the tool. During the implementation of the bristle blasting process, the operator can in fact apply a low, medium or high pressure, on the work part. The different amount of pressure the operator applies will affect the results of the process, in this case the amount of material removed. Hence, three different penetration depths have been chosen to simulate a low, medium and high operating pressure. These penetration depths are 0.1, 0.15 and 0.2 inches. Table 3.1 show the experiments matrix of the configurations (tool age / penetration depth) that were run for each material system.
Table 3.1: Material removal experiments matrix.

<table>
<thead>
<tr>
<th>Tools age [min.]</th>
<th>Penetration Depth [in.]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>New</td>
<td>ABS-A</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>ABS-A</td>
</tr>
</tbody>
</table>

3.2.3. Material Removal Study Results

The first material system subject to the material removal study was steel ABS-A. This material system was tested at three different penetration depths (0.1, 0.15 and 0.2 inches.) and in combination with three different tool ages, “new” (as-received), and tools with 25 minutes and 60 minutes of continuous use. Figures 3.2 through 3.4 show the capability that the bristle blasting tool has for material removal performance on steel ABS-A as the tool ages, from “new” to 25 minutes to 60 minutes of continuous use, at set penetration depths (0.1, 0.15 and 0.2 inches respectively) as mentioned above. Figures 3.5 through 3.7 show the effect that different penetration depths, 0.1, 0.15 and 0.2 inches have at a set tool age mentioned above.

After testing the ABS-A steel, the study moved on to the AH-36 steel. However, this material system prove to be very challenging to work on for the bristle blasting tool. Due to the challenging condition and harshness that the AH-36 material system imposed on the bristle blasting tool, the material removal studies were conducted at a set penetration depth of 0.2 inches. This depth was the only penetration depth where reliable/
repeatable data could be recored. Due to the extremely fast deterioration of the bristles, as they work on the AH-36 material system, four different tools with different service life were used. The material removal data for steel AH-36 was obtain for a “new” (as-received) tool and tools with 5, 25 and 60 minutes of continuous service, at a set penetration depth of 0.2 inches as mention before. Figure 3.8 shows the results for the previously described material removal study for steel AH-36.

In an effort to quantify the difference in the material removal performance of the bristle blasting between steels ABS-A and AH-36, comparison plots were generated. Figures 3.9, 3.10 and 3.11 show a comparison in the material removal performance at a set penetration depth of 0.2 inches and for specific aged tools of new or as-received, 25 and 60 minutes respectively.

3.2.4. Discussion of Material Removal Study Results for Steels ABS-A and AH-36

As mentioned previously Figures 3.2 through 3.4 show the capability of the bristle blasting tool for material removal performance on steel ABS-A as the tool ages, from “new” to 25 minutes to 60 minutes of continuous use, at set penetration depths (0.1, 0.15 and 0.2 inches respectively). The data depicted on these Figures show the effect that tool aging has on the material removal performance of the bristle blasting process. From these three figures it is appreciable that as the bristle tool ages the material removal capacity of the tool decreases and thus sets life for the tool of 60 minutes.
Figures 3.5 through 3.7 illustrate the data collected for a specific aged tool (new, 25 minutes or 60 minutes) as the penetration depth of the tool varies from 0.10 inches, 0.15 inches and 0.20 inches, on steel ABS-A. The results on these Figures show an important behavior of the bristle blasting tool. The graphs clearly indicate that as the penetration depth increases, the material removal on the specimen increases as well. More importantly Figures 3.6 and 3.7 demonstrate that as the tool ages, low penetration depths results in very poor material removal performance. For instance, in Figure 3.6, the 25 minute tool had little to virtually no material removal capability at a penetration depth of 0.10 inches, however, at 0.15 and 0.20 inches the tool performed adequately. A similar behavior is portrayed in Figure 3.7, where the 60 minute tool was only able to achieve a decent material removal capability at a penetration depth of 0.20 inches. These result show a correlation between the aging of the tool and the penetration depth that must be considered in order to have a promising material removal capability on steel ABS-A.

Figure 3.8 shows the material removal data collected for steel AH-36. Four different aged tools were used to collect the material removal data for steel AH-36, and a set penetration depth of 0.20 inches was chosen. The data in the graph, shows how quickly the material removal capability of the tool deteriorates on steel AH-36. The ‘new’ and 5 minute tool show a promising material removal performance. Nevertheless, when the tool reaches the 30 minute mark of continuous use, the material removal capabilities are considerably decreased. Both the 30 and 60 minute aged tools displayed a
poor material removal performance on steel AH-36, even at an aggressive 0.20 inch penetration depth.

In an attempt to compare the material removal performance of the tool on steels ABS-A and AH-36, Figures 3.9 through 3.11 were created. These Figures show the performance of the tool on both steels ABS-A and AH-36 at a set penetration depth of 0.20 inches and the implementation of a tool with the same time of continuous use (5, 25 or 60 minutes). The Figures make it clear that the bristle blasting tool has a far superior material removal performance on steel ABS-A than on steel AH-36. In fact, as outlined in Table A.1, the material removal rate of the tool on steel ABS-A is more than twice that on AH-36, regardless of the age of the tool.

3.3. Surface Texture and Assessment of Tool Life

3.3.1. Introduction to Surface Texture and Assessment of Tool Life

A key metric in the evaluation of a successful application for the bristle blasting process is the surface texture finish that the process creates on the working part. As mentioned before, one of the main goals the bristle blasting process has is the creation of a rough surface profile commonly known in the industry as an anchor profile. To be able to quantify and assess the success of the bristle blasting process a measurement of the morphology of the surface must be made. Therefore, a host of surface texture parameters have been proposed for quantifying the architectural characteristics of the surface with a
higher degree of precision. To achieve this metric, the average peak-to-valley texture parameter $R_z$ was used to quantify the anchor profile of the cleaned surface. The $R_z$ value is often used as a measure, on cleaned surfaces, to ensure the proper adhesion of paints and coatings prior to their application. Therefore, this metric is a key element in the success implementation of the bristle blasting process on a material system.

3.3.2. Experimental Set-Up and Procedure for Surface Texture and Assessment of Tool Life

To assess the performance of the bristle blasting process in creating a successful anchor profile on the materials under investigation in this study (steels ABS-A and AH-36), various surface texture procedures were carried out. These surface texture procedures were:

- Single Manual Pass by a trained operator,
- Plastic Deformation Microscopy Investigation,
- Leading Edge $R_z$ Values, and
- Aging of Tool vs. $R_z$ Measurement.

Steel ABS-A was subject to all of the above procedures. However steel AH-36 was only subject to the first two experimental procedures, due to its poor performance, which will be discussed in a later section.

The Single Manual Pass by a trained operator procedure consisted of creating a single manual pass with the bristle blasting tool on to a previously designated cleaned
machined ground surface material coupon (either steel ABS-A or AH-36). The operator was instructed to create three single horizontal bands by applying a low, medium and high pressure between the tool and the specimen. This allows one to assess the tool’s performance at different depths, as the operator may exert a range of pressure between the tool and the work-part to obtain the desired surface texture. During this experiment, four different tools with four different amounts of accumulated service time were used, namely a new (as received) tool, a 5 minute tool, a 25 minute tool and a 60 minute tool. Each of these four tools were applied by the operator at low, medium and high depths as mentioned above. Immediately after the material sample is bristle blasted with a specified aged tool, the surface texture parameter $R_z$ was measured using a standard surface roughness tester, (Mitutuyo Surface Roughness Tester SurfTest SJ-301). The parameters settings of the SurfTest SJ-301 to obtain the surface texture reading were a Standard ISO 1997, 5 sampling lengths and $\lambda_C = 2.5 \text{ mm}$. Three measurements of the $R_z$ value were taken on each single pass path and recorded to be average for the data tabulation.

Following the Single Manual Pass experiment, samples for the Plastic Deformation Microscopy Investigation were prepared. The Plastic Deformation Microscopy Investigation consisted of a bristle blasting surface of each material in question (steels ABS-A and AH-36) with a new or as received tool. The entire surface of the specimen was bristle blasted as described in Section 1.3.3, Implementation of the bristle Blasting Process. Once the bristle blasting process was completed, a small area of the specimen was cut out to create a mounted specimen for the microscopy analysis. The
small cut-out of the specimen was mounted into a two part epoxy system and cured for 8 hours in a vacuum. After the epoxy had cure the mounted specimens were ground with sand paper to obtain a flat surface and then polished with 1.0 or 0.05 µm aluminum oxide powder. When a mirror like polish was achieved on the specimens, these were etched using a 3% Nital solution.

Having mounted, polished and etched both ABS-A and AH-36 specimens, were examined with a light microscope to see the effect that the bristle blasting process had on the surface. Various digital photographs were taken at 400x and 1000X, focusing on the edge area of the specimens. The edge area is the focus of this experiments, since the objective of this experiment is to investigate the material behavior, at a microscopic level, after it has undergone the bristle blasting process.

To develop a detailed understanding of the surface texture that is generated by the bristle blasting process, a third texture study was created called the Leading Edge $R_z$ Values. For this experimental study bristle blasted surfaces are prepared by a manual, user-applied steady load as depicted in Figure 1.17 and following the procedure described in Section 1.3.3. That is, the specimen, with a machined finished surface, was subjected to a single pass (that is, a single horizontal band), and the surface texture parameter $R_z$ within the band was subsequently measured at several uniformly-spaced sampling positions that lie along the direction of tool movement using the Mitutuyo Surface
Roughness Tester SurfTest SJ-301. Figure 3.19 shows the specimen setup for this experiment as well as the markings and guides to follow to for the data recordings.

During this texture study four tools with different duty life cycles, namely, ‘new’ (as-received), 5 minute, 25 minute and a 60 minute tools were used. Apart from the different tool duty cycles used in the experiment, three single pass bands were made with each tool at three different penetration depths, low, medium and high penetration. For each pass the $R_z$ values were taken. As mentioned above, this particular texture study was only carried-out on steel ABS-A due to the lack of texture performance (very low $R_z$ values) of the tool on steel AH-36, which will be discussed in a later section.

As one may expect, the texture generated by bristle blasting tools will vary as the duty cycle of the tool increases due to filament tip wear and/or breakage. Hence the Aging of Tool vs. $R_z$ Measurement texture study was developed. In this study, the tool performance over time is examined by manually cleaning a corroded ABS-A sample (Figure 3.12) and periodically measuring $R_z$ using standard press-film replica tape. Thus, a relationship between duty cycle and profile performance of the tool can be examined. Press-film replica tape is a common measuring technique to determine surface texture roughness out in the field.

To initiate this texture study a brand new (as-received) tool was used in the process of cleaning heavily corroded specimens of steel ABS-A. Surface profile, $R_z$,
measurements were taken in 5 minute intervals, and the tool was always working on corroded surfaces, i.e., simulating true working conditions. The surface roughness measurements were taken until the tool had a service life of 60 minutes. Again, as mention before, this texture study was only conducted on steel ABS-A.

3.3.3. Results for Surface Texture and Assessment of Tool Life

As previously mentioned, the surface texture studies play a key role in the assessment of the performance of the bristle blasting process on a specific material system. To start assessing the tool’s performance on steel ABS-A and AH-36 a single manual pass by an operator was performed, as described above. Figures 3.13 and 3.14 show the surface texture results in terms of $R_z$ (microns) versus the tool’s service life in minutes of service, for three different penetration depths, low, medium, and high. The results for steel ABS-A can be found in Figure 3.13, and Figure 3.14 shows the results for steel AH-36.

The main objective of the Plastic Deformation Microscopy Investigation was to show the effect that the bristle blasting process had at a microscopic level on the work surface. More so, the results objective was to achieve an illustration of the granular structure at the surface of the worked part after it has been subjected to the bristle blasting process. Two microscopic photographs were taken for each material system, one at 400X magnification and another at 1000X magnification. Figures 3.15 and 3.16 show the effects, at a microscopic level, of the bristle blasting process for steel ABS-A at 400X and
1000 X respectively. The effects, at a microscopic level, for steel AH-36 can be observed in Figures 3.17 and 3.18, at 4000X and 1000X magnification, respectively.

To have a better understanding of the surface texture profile that is generated by the bristle blasting process, the Leading Edge $R_z$ experiment aids in the understanding of the surface roughness topography. Four different sets of results were generated from the $R_z$ data that was collected. Figures 3.20 through 3.23 show the surface roughness topography, in terms of $R_z$ (in microns), as the width of the bristle blasted band increases. Hence, as the distance $S$ (in inches) form the leading edge, created by the tool increases. The four different Figures (3.20 through 3.23) show the results of the Leading Edge $R_z$ study with each of the four different ‘aged’ tools (‘new’, 5 minute, 25 minute and 60 minute) used in this experiment as described above. Each figure also shows the three different user-applied penetration depths, namely, low (blue diamond), medium (red square) and high (green triangle).

The results of the Aging of Tool vs. $R_z$ Measurement study can be seen in Figure 3.24. The results from this experiment show the variation in texture, that the bristle blasting process creates, as the tool ‘ages’ or goes through its life service cycle. Figure 3.24 evaluates the anchor profile created by the bristle blasting tool in terms of $R_z$ (in microns) and how it varies due to filament tip wear and/or breakage as the tools duty cycle increases through time. Thus the relationship between duty cycle and profile performance is shown mimicking a real life application.
3.3.4. Discussion of Results for Surface Texture and Assessment of Tool Life

The graph in Figure 3.13 shows the surface roughness generated by the bristle blasting tool on steel ABS-A and illustrates how the age of the tool affects the capability of the tool to create a rough surface on this steel. Three different penetration depths were used (low, medium and high) to collect the surface roughness data. The bristle blasting tool was able to achieve $R_z$ values above 100 $R_z$ microns and maintain a minimum $R_z$ value of 60 $R_z$ microns after 60 minutes of continuous use, this achievement will be greatly welcome out in the field.

An interesting point about the data collected in Figure 3.13, is that, although the results for the three different penetration depths are very close together, when the tool is at a ‘new’ stage of its life, the low penetration depth creates the highest $R_z$ value. Whereas the tool ages with time of use, the deeper penetration depths are able to create better $R_z$ results, giving the operator the ability to vary the force applied to the tool in order to achieve the desire penetration depth and, hence, obtain a successful surface roughness profile.

For steel AH-36 the bristle blasting tool was able to achieve a maximum of 63 $R_z$ microns when the tool was brand new, but unfortunately the surface roughness $R_z$ value dropped dramatically, below 30 $R_z$ microns, after just five minutes of use of the tool. From that point on, the $R_z$ reading for the 25 and 60 minute tool oscillated between the 20-30 $R_z$ microns, regardless of the penetration depth applied by the tool on the AH-36
The Plastic Deformation Microscopy, in Figures 3.15 through 3.18, show interesting characteristics of the consequences that the bristle blasting process produce on steels ABS-A and AH-36. As mentioned before, the microscopy samples were created using a ‘new’ or as received tool. Figures 3.15 and 3.16 show a microscopic view of an ABS-A bristle blasted surface looks like. In both photographs one can see a significant layer of plastically deformed material at the edge of the specimen. This plasticly deformed layer is an indication of the surface roughness performance that the bristle blasting tool has on steel ABS-A, hence, it demonstrates that the bristles are able to create small craters by the unique impact and shoveling technique that the bristle blasting tool has on the work surface. Being able to plastically deformed the work part surface and create the craters with ease, leads to a higher surface roughens results and making the bristle blasting process a success.

The photo microscopy of a bristle blasted AH-36 specimen are shown in Figures 3.16 and 3.17. Unlike steel ABS-A, there is no appreciable band of plastic deformation in the materials grains. The fact the there is no band of plastic deformation at the surface of the material, could be the reason why the bristle blasting process has a poor surface roughness performance on steel AH-36, as mentioned previously in the analysis of Figure 3.14. Not being able to create the signature small craters of the process and deform the
material at the surface of the specimen; results in poor surface roughness results, making the bristle blasting process not very adequate for this type of material.

Figures 3.20 through 3.23 show the results for the leading edge $R_z$ study. The leading edge study, as previously mentioned, shows the width of the band that the bristle blasting tool is creating on the surface by measuring the $R_z$ value across the band. Each Figure, from 3.20 through 3.23 is for a specifically aged tool; new, 5, 25 and 60 minutes. What we can take away from this particular study is that, as the bristle tool ages, the width of the band created on a specimen’s surface diminishes. This means that a newer tool creates a wide and aggressive surface roughness profile, and as the tool ages, the band gets narrower and the surface roughness profile decreases.

The last study conducted assesses the Surface Texture and Assessment of Tool Life is the Aging of Tool vs. $R_z$ Measurement. As described previously, this study was designed to simulate conditions out in the field and the results one would see in data collected with the equipment that is used in the field. The results obtained during this study correlate well with results collected during the Single Manual Pass by an Operator study (See Figure 3.13). The surface roughness $R_z$ values collected when the tool is in it’s ‘new’ stage averaged 80 $R_z$ microns and by the end of the tool life, 60 minutes of use, the surface roughness averaged 52 $R_z$ microns. The pattern between the surface roughness $R_z$ value and the age of the tools is very closed to the ones collected with the profilometer
and the data shown in Figure 3.13. This study proofs again that the bristle blasting process could be very well implemented out on the field.

3.4. Cleanliness and Texture of Bristle Blasted Treated Surfaces

3.4.1. Introduction to Cleanliness and Texture of Bristle Blasted Treated Surfaces

Although the effectiveness of the bristle blasting procedure is mainly quantified by its performance in the material removal studies and the surface texture studies; one of the main objectives of the bristle blasting tool is also to effectively remove corrosion and clean surfaces affected by such attack. While the material removal studies demonstrate the ability of the tool to remove surface material, it was important to demonstrate in this study, the tool’s capacity for corrosion removal and surface cleaning as well. The objective of this corrosion removal and cleanliness study is to show the effectiveness to the bristle blasting process in a more realistic and ‘field like’ scenario.

3.4.2. Experimental Set-Up and Procedure for Cleanliness and Texture of Bristle Blasted Surfaces

Given that the objective of the cleanliness study for the bristle blasting process is to simulate ‘field’ conditions, heavily corroded ABS-A steel plate samples were obtained. Figure 3.12 shows a sample of the severely corroded ABS-A steel plate that was used for evaluating the corrosion removal performance of the bristle blasting tool. A careful examination of the ABS -A specimen shown in Figure 3.12 indicates that the surface is
comprised of a thick corrosive layer which is accompanied by significant pitting. Consequently, SSPC Condition D (100% rust with pits)\textsuperscript{23} appears to provide an accurate assessment of the initial severity of corrosion that has formed on the surface.

Three different bristle blasting tools, ‘new’ (as-received), 25 minute and a 60 minute, were used to assess the corrosion removal capabilities of the process. Each tool was used to clean a corroded specimen of ABS-A steel such as the one shown in Figure 3.12. After an area of approximately 10 cm by 5 cm of the corroded specimen was cleaned, the cleaned area was cut and section into a smaller samples suitable for examination in a scanning electron microscope (SEM). The bristle blasted specimens were photographed at a macroscopic level as well as under the examination of the scanning electron microscope.

3.4.3. Results for Cleanliness and Texture of Bristle Blasted Treated Surfaces

The macroscopic pictures of the corroded ABS-A specimen, post-bristle blasting, show a clear indication of the corrosion removal and cleaning capabilities of the bristle blasting process. Figure 3.25 shows the initially corroded surface (top) along with a cleaned portion of the specimen after bristle blasting for comparison (bottom). Further inspection of these surfaces is shown at higher magnification in Figure 3.26a and 3.26b.

During the examination under the SEM various photographs at different magnifications were taken of the bristle blasted sample and documented. Figure 3.27
through 3.29 show the topography under the SEM of the ABS-A specimen after being bristle blasted with a ‘new’ (as-received) tool. The topography of the specimen treated with a 25 minute old tool can be seen in Figures 3.30 through 3.32. Lastly, the cleaning results of the 60 minute tool can be viewed in Figures 3.33 through 3.36. All of the SEM figures will be discussed and analyzed in greater detail in a later section of this study.

3.4.4. Discussion of Results for Cleanliness and Texture of Bristle Blasted Treated Surfaces

The macroscopic pictures shown in Figures 3.26a and 3.26b depict the before and after bristle blasting condition of a heavily corroded sample of steel ABS-A. The difference in cleanliness is very obvious. The corrosion grade of the ABS-A sample has been assessed to SSPC Condition D (100% rust with pits), as mentioned before. While the bristle blasted treated area denotes an almost white metal cleanliness condition.

Although the macroscopic photographs show excellent cleanliness results, it is important to observe the treated surfaces at a microscopic level. Figures 3.27 through 3.36 show scanning electron microscope photographs of ABS-A samples that have cleaned using ‘new’, 25 minute and 60 minute tools. These photographs of the cleaned surfaces show both the exposed substrate metal and the detailed surface texture. Careful examination of these images reveal that the surfaces are free of residual corrosion and that the characteristic impact craters appearing in Figure 1.13 (i.e., shovel micro-
indentation) appear as a repeated pattern along the cleaned surfaces of these ABS-A samples.

A direct comparison can now be made between the cleanliness of surfaces generated by the bristle blasting process with those published by the Society for Protective Coatings (SSPC) for power hand tools (SSPC VIS 3)\(^ {24} \). Such a comparison clearly indicates that the surfaces generated by the bristle blasting process surpass the cleanliness that is characteristic of all power tool cleaning processes, including hand tool cleaning by power brushes, sanding discs, and needle guns. The cleanliness of the surfaces produced by bristle blasting is also better than the cleanliness and texture expectations that are typical of power tool cleaning to bare metal, as cited in SSPC standard SP 11. That is, SP 11 allows corrosion to remain at the bottom of pits and has a minimum surface profile requirement of 25 microns, whereas no corrosive pits remain after bristle blasting, and the surface profile typically varies from 52 to 80 microns, as demonstrated in the previous section. Comparison can also be made between the bristle blasting process and the dry abrasive blast cleaning standards, namely SSPC VIS 1\(^ {25} \). Careful examination of SSPC photographs for these visual standards indicates that the cleanliness performance of the bristle blasting process exceeds that of brush-off blast cleaning (SP 7), industrial blast cleaning (SP 14), and commercial blast cleaning (SP 6). The thoroughness of the bristle blasting process, however, does appear to be comparable with near-white blast cleaning (SP 10) and white metal blast cleaning (SP 5).
Figure 3.1: Experimental set-up for the material removal studies (Ref. 26).

Figure 3.2: Measured material removal for ABS-A steel at 0.1” penetration depth, using different bristle blasting tools with various periods of continuous service. Approximate bristle tool specifications: face width: 22 mm, hub radius: 27.5 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480.
Figure 3.3: Measured material removal for ABS-A steel at 0.15” penetration depth, using different bristle blasting tools with various periods of continuous service. Approximate bristle tool specifications: face width: 22 mm, hub radius: 27.5 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480.

Figure 3.4: Measured material removal for ABS-A steel at 0.2” penetration depth, using different bristle blasting tools with various periods of continuous service. Approximate bristle tool specifications: face width: 22 mm, hub radius: 27.5 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480.
Figure 3.5: Measured material removal for ABS-A steel, using a bristle blasting tool in a “new” or as received condition at different depths of penetration. Approximate bristle tool specifications: face width: 22 mm, hub radius: 27.5 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480.

Figure 3.6: Measured material removal for steel ABS-A, using bristle blasting tool having a 25 minute duty cycle at different depths of penetration. Approximate bristle tool specifications: face width: 22 mm, hub radius: 27.5 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480.
Figure 3.7: Measured material removal for steel ABS-A, using bristle blasting tool having a 60 minute duty cycle at different depths of penetration. Approximate bristle tool specifications: face width: 22 mm, hub radius: 27.5 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480.

Figure 3.8: Measured material removal for AH-36 steel at 0.2” penetration depth, using different bristle blasting tools with various periods of continuous service. Approximate bristle tool specifications: face width: 22 mm, hub radius: 27.5 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480.
Figure 3.9: Material removal comparison of steel ABS-A vs. AH-36. Penetration depth 0.2 inches with a tool accumulated duty cycle of 5 minutes.

Figure 3.10: Material removal comparison of steel ABS-A vs. AH-36. Penetration depth 0.2 inches with a tool accumulated duty cycle of 25 minutes.
Figure 3.11: Material removal comparison of steel ABS-A vs. AH-36. Penetration depth 0.2 inches with a tool accumulated duty cycle of 60 minutes.

Figure 3.12: Corroded section of ABS-A steel plate used for evaluating corrosion removal performance and surface texture roughness of the bristle blasting tool (Ref. 1).
Figure 3.13: Single manual pass by an operator surface texture results, Rz (microns) vs. Tool service life (minutes) for steel ABS-A at three different penetration depths.

Figure 3.14: Single manual pass by an operator surface texture results, Rz (microns) vs. Tool service life (minutes) for steel AH-36 at three different penetration depths.
Figure 3.15: Microscopic photograph of steel ABS-A after undergoing bristle blasting process.

Figure 3.16: Microscopic photograph of steel ABS-A after undergoing bristle blasting process.
Figure 3.17: Microscopic photograph of steel AH-36 after undergoing bristle blasting process.

Figure 3.18: Microscopic photograph of steel AH-36 after undergoing bristle blasting process.
Figure 3.19: Leading Edge Rz specimen setup and guidelines (Ref. 2).

Figure 3.20: Measured surface profile with a ‘new’ tool for steel ABS-A, at several locations within the contact region bandwidth for a single pass, at different penetration depths for the bristle blasting process.
Figure 3.21: Measured surface profile with a 5 minute aged tool for steel ABS-A, at several locations within the contact region bandwidth for a single pass, at different penetration depths for the bristle blasting process.

Figure 3.22: Measured surface profile with a 25 minute aged tool for steel ABS-A, at several locations within the contact region bandwidth for a single pass, at different penetration depths for the bristle blasting process.
Figure 3.23: Measured surface profile with a 60 minute aged tool for steel ABS-A, at several locations within the contact region bandwidth for a single pass, at different penetration depths for the bristle blasting process.

Figure 3.24: Results for Aging of Tool vs. Rz Measurement study for steel ABS-A. Surface profiles were recorded using standard press-film replica tape. Approximate bristle tool specifications: face width: 22 mm, hub radius: 27.3 mm, bristle wire diameter: 0.73 mm, bristle length: 27 mm, total bristle population ~480 (Ref. 1).
Figure 3.25: Initial corroded surface of as-received ABS-A specimen prior to cleaning (top) and after bristle blast cleaning (bottom) (Ref. 1).

Figure 3.26: (a) Photograph depicting the extent of corrosion/pitting on the as-received surface of piping, and (b) cleanliness of the bristle blasted surface after corrosion removal (Ref. 1).
Figure 3.27: Scanning electron micrograph (magnification 20x) of ABS – A steel treated surface. Bristle tool duty cycle: 0 min.

Figure 3.28: Scanning electron micrograph (magnification 50x) of ABS – A steel treated surface. Bristle tool duty cycle: 0 min.
Figure 3.29: Scanning electron micrograph (magnification 50x) of ABS –A steel treated surface. Bristle tool duty cycle: 0 min.

Figure 3.30: Scanning electron micrograph (magnification 20x) of ABS –A steel treated surface. Bristle tool duty cycle: 25 min.
Figure 3.31: Scanning electron micrograph (magnification 50x) of ABS – A steel treated surface. Bristle tool duty cycle: 25 min.

Figure 3.32: Scanning electron micrograph (magnification 50x) of ABS – A steel treated surface. Bristle tool duty cycle: 25 min.
Figure 3.33: Scanning electron micrograph (magnification 20x) of ABS – A steel treated surface. Bristle tool duty cycle: 60 min.

Figure 3.34: Scanning electron micrograph (magnification 50x) of ABS – A steel treated surface. Bristle tool duty cycle: 60 min.
Figure 3.35: Scanning electron micrograph (magnification 20x) of ABS –A steel treated surface. Bristle tool duty cycle: 60 min.

Figure 3.36: Scanning electron micrograph (magnification 50x) of ABS –A steel treated surface. Bristle tool duty cycle: 60 min.
Figure 3.37: Microscopic photograph of steel ABS-A.

Figure 3.38: Microscopic photograph of steel ABS-A.
Figure 3.39: Microscopic photograph of steel AH-36.

Figure 3.40: Microscopic photograph of steel AH-36.
4. BRISTLE BLASTING TOOL PERFORMANCE ON WELDED JOINTS FABRICATED FROM COMMERCIAL SHIP CONSTRUCTION STEEL

4.1. Weld Joints Fabricated from Commercial Ship Construction Steel

During the repair and maintenance of steel structures of marine vessels, engineers exercise great care in producing and protecting welded joints, because the integrity of these seams provides a cornerstone for ensuring the vessels structural longevity. At the same time, maintenance engineers in the ship building industry are faced with the continual need for deploying new methods for surface preparation that will not compromise the surface cleanliness and anchor profile requirements that are necessary for proper adhesion of paints and coatings.

In this section the recently developed bristle blasting process is used for cleaning and preparing welded joints fabricated from both ABS-A and AH-36 steel, which are commonly used in the commercial ship building industry. The performance of the bristle blasting process on the weld seams will be evaluated within the context of both cleaning and simultaneously generating a receptive anchor profile along the seam of welded joints. The aggressiveness and material removal capacity of the tool is measured and reported using standard tool operating conditions, and the texture and surface morphology generated by the bristle blasting process is examined along the crown and toe of the weld. Finally, the overall cleanliness of surfaces generated by bristle blasting is assessed by a
Prior to evaluating the bristle blasting process on welded seams, it is important to understand the characteristics and structure of the weld seams samples used in this study at a macroscopic and microscopic level.

**4.1.1. Characteristics of As-Received Welded Joints**

ABS-A and AH-36 steel welded plates were supplied to conduct the evaluation of the bristle blasting process on welded seams. The weld samples in the as-received condition consisted of, approximately, 10 inch by 3.5-4 inch plates that had been welded together by a butt weld joint design. In each plate the welding was performed on both sides of 0.5 in. (1.3 cm.) thick plate using a wire feed machine, and the filler/rod metal used was Lincoln 71M, with CO$_2$ shielding gas. Figures 4.1a and 4.1b show the ABS-A plate and Figure 4.2a and 4.2b show the AH-36 plate samples for the study.

Figure 4.1a illustrates the weld bead on the front side of the ABS-A, which depicts typical spatter and slag that is commonly generated during the formation of welded joints. The contour of the weld pool is magnified in Figure 4.1a (red inset) and exhibits typical weld-flow/solidification lines. The reverse side of the ABS-A welded plate is shown in Figure 4.1b, which exhibits similar characteristics as its counterpart.
In Figure 4.2a, the front weld bead of the AH-36 plate is shown the weld spatter, slag, and the contour of the weld pool (red inset) are similar to those shown for ABS-A plate. Figure 4.2b shows the reverse side of the AH-36 plate, the weld pool in this case seems narrower. Both plate materials exhibit minimal corrosion, since the specimens were not subjected to a corrosive environment for an extensive time duration.

To understand the microstructure of the welded specimens, metallographic profile/cross sections of both ABS-A and AH-36 welded joints were prepared. The ABS-A welded joint is shown in Figure 4.3 along with the microstructure of the top weld bead, bottom weld bead, and parent material which flanks both sides of the joint. The top and bottom weld microstructure in Figure 4.3 are typical of the low carbon weld rod (Lincoln 71M) used. Both welds exhibited a dendritic pattern of ferrite grains with fine and coarse grain structures. The bottom weld bead exhibited a finer grain structure, which is reflected in slightly higher Vickers (500 gm. load) micro-hardness values, averaging 188 on the Vickers hardness scale, as shown in Figure 4.5b. The top weld, Figure 4.5a, averages 161 on the Vickers hardness scale. The microstructure of the ABS-A base metal is typical of good quality hot-rolled low-carbon steel, and rendered an average Vickers hardness measurement of 155, which is 4-18% less than the weld bead measurement. It consists of grains of ferrite with some regions of pearlite, and does not exhibit excessive banding.
The top and bottom weld microstructure for the AH-36 shown in Figure 4.4 are typical of the low carbon weld rod (Lincoln 71M) that was used. Both welds exhibited a dendritic pattern of ferrite grains with coarse and fine grain structures like the ones present on the ABS-A plate. The bottom weld bead again exhibited a finer grain structure, which is reflected by a slightly higher Vickers micro-hardness, averaging 184 on the Vickers hardness scale, as shown in Figure 4.6b. The top weld, Figure 4.6a, averages 168 on the Vickers hardness scale. The microstructure of the AH-36 base metal is typical of hot-rolled low-carbon steel once again, but resulted in a slightly higher average Vickers hardness measurement of 182, which is 0-10% more than the weld bead measurement. It exhibited a higher degree of banding than the ABS-A, but it is not viewed as excessive.

A popular weld joint design is the T-joint, where two different plates are welded 90 degrees to each other. Samples of both ABS-A and AH-36 T-joints were supplied to the lab. Figures 4.7 and 4.8 show the initial condition of the supplied T-joints for steel ABS-A and AH-36 respectively.

4.2. Material Removal Studies of Welded Joints

4.2.1. Introduction to Material Removal Studies of Welded Joints

As mentioned before in section 3.2.1, the material removal performance of the bristle blasting process is a key metric in evaluating the process success and efficiency. The material removal experiment will show the ability of the bristle blasting tool to
remove corrosive material layers as well as base parent material of the work part. This experiment will also assess the material removal performance of the bristle blasting tool as it ages through time. Most importantly, one will be able to compare the material removal performance of the tool on weld seams to its performance on parent materials (ABS-A and AH-36) from the previous results obtained in this study and reported in section 3.2.3.

4.2.2. Experimental Set-Up and Procedure for Material Removal Studies on Welded Seams

The set-up and procedure used for the material removal experiments on the weld seams is very similar to the procedure and set-up of the material removal experiments on steels ABS-A and AH-36, described in Section 3.2.2. The set-up shown in Figure 3.1 illustrates the overall architecture used for the material removal studies, in this case, the specimen put in place was that of a welded joint. The specimen was placed with the intention that the bristles of the tool would interact with the weld seam only; ensuring that the material removed belonged to the weld seam or weld pool.

Material removal specimens for weld seams fabricated on steel ABS-A and AH-36 are shown in Figures 4.9a and 4.9b respectively, which show the exact contact region where bristle tips have traversed the weld bead. Careful examination of each Figure indicates that the uppermost portion of the weld remains untouched by the tool, whereas the crown of the weld bead corresponds to the primary impact site of bristle tips.
Furthermore, lower portions of the weld bead as well as a segment of the parent base metal bear secondary impact craters, which are indicative of subsequent (less formative) “rebounds” of the bristle tip. Finally, it is apparent that bristle tips have not engaged the lower region of the weld toe, because “down-stream” portions of the contact zone are partially masked by higher elevations of the weld itself. In summary, based upon the observed tool contact pattern shown in Figures 4.9a and 4.9b, it is conjectured that the material removed (gram-weight) from the contact region will largely be associated with the weld bead itself, whereas the secondary contact of bristle tips with the base metal surface will play a minimal role in the material removal process.

The material removal experiments for the welded joint specimens were carried out using two sets of bristle blasting tools. The experiments were conducted first with a ‘new’ (as-received) tool on both ABS-A and AH-36. Thereafter a tool with a duty cycle of 25 minutes was used on another set of welded coupons of ABS-A and AH-36. Due to the small number of welded samples, the material removal experiments were only conducted at 0.2 inches of penetration depth. The 0.2 inch penetration depth was chosen, since in the previous material removal studies, it was the penetration depth that created optimal results. This penetration depth will also allowed the comparison of the material removal performance on the parent material (ABS-A and AH-36) to the material removal on the weld seam. The amount of material each specimen lost was recorded using a high sensitivity scale, and the data was plotted as outlined in the next section.
4.2.3. Results for Material Removal Studies on Welded Seams

Just as in Section 3.2.3, graphical plots were generated to quantify the performance of the bristle blasting tool in the material removal process. Figure 4.10 shows the results for the material removal experiment on steel ABS-A. In this Figure, the results for both a ‘new’ (as-received) and 25 minute old tools are displayed for comparison purposes. Figure 4.11 shows the same set of results but for the material removal process on steel AH-36.

Data obtained during the material removal studies in section 3.2 is used to help assess the relative performance of bristle blasting tools when used for cleaning base metal (parent material) in comparison with the welded joint material. Thus, a direct comparison of these two different material removal processes is shown in Figures 4.12 through 4.15 for ABS-A and AH-36 steels. Figures 4.12 and 4.13 show the material removal comparison using a ‘new’ (as-received) tool for steels ABS-A and AH-36. Figures 4.14 and 4.15 show the material removal comparison using a tool that has undergone 25 minutes of continuous use for steels ABS-A and AH-36 respectively.

Further investigation was carried out with the collected data to gain a deeper knowledge of material removal performance of the bristle blasting tool on welded seams. Fortunate, with the consistency of the data collected in the material removal experiments for the welded seams, the study is able to present the material removal rate (in grams/second) of the bristle blasting tool, on welded seams, as a function of time (in seconds).
Figures 4.16 and 4.17 show the material removal rate on steel ABS-A and AH-36 respectively, for both ‘new’ (as-received) and 25 minute old tools. These figures portray the effects that tool aging have on the material removal rate performance on steels ABS-A and AH-36 respectively. In an effort to illustrate a full comparison and comprehensive picture, Figures 4.18 and 4.19 show the material removal rate performance of, a new (as-received) tool and 25 minute old tool, respectively, and their comparative performance on steels ABS-A and AH-36 side by side. All of the portrayed data from this section will be discussed and analyzed in the next section.

4.2.4. Discussion of Results for Material Removal Studies on Welded Seams

The material removal studies on welded seams were carried out using two different aged tools, new and 25 minutes old, as mentioned previously. The results for the material removal on welded seams for both ABS-A and AH-36 are displayed in Figures 4.10 and 4.11. The portray data in the Figures show a decline in material removal performance, which is attributed to the progressive wear of bristle tips as the tool accrues duty cycles associated with repetitive impact as the tool ages. It is important, however, to mention that the material removal performance for the 25 minute tool used on steel AH-36 has a significant lower performance that the tool used on steel ABS-A. This behavior correlates to the performance seen on the studies carried in section 3.2.

To help assess the relative performance of bristle blasting tools when used for cleaning welded seams, the data collected in section 3.2 (material removal of base metal)
is used as a comparison. Figures 4.12 through 4.15 show a direct comparison of these two different material removal processes for both ABS-A and AH-36 steels. In each case, the results are shown for as-received bristle blasting tools and indicates that material removal performance is essentially unchanged for ABS-A (see Figure 4.12), whereas weld bead material removal occurs at nearly twice the rate of parent material for AH-36 steel (See Figure 4.13.). This result is intriguing, and the findings are again repeated for bristle blasting tools that have acquired 25 minutes of continuous use in Figures 4.14 and 4.15.

Examination of these results indicates that, once again, the material removal performance is essentially unchanged for ABS-A (see Figures 4.12 and 4.14), whereas weld bead material removal occurs more rapidly (approximately 15%) than that of parent material for AH-36 steel (see Figures 4.13 and 4.15). In summary, these results indicate that both the weld and parent material of ABS-A steel are uniformly/equally abraded during the surface preparation process, whereas the weld bead material of AH-36 steel is preferentially abraded when compared to parent material during the surface preparation process. This propensity for greater material removal along the weld bead (AH-36 steel only) suggests that weld/spatter cleaning inevitably occurs more rapidly than of base metal, thereby leading to preferential weld cleaning and reduced process time.

From the material removal data of the weld seams, it was possible to calculate the material removal rate of the weld seams. Figures 4.16 and 4.17 show the material removal rate results of welded seams for both steel ABS-A and AH-36 respectively.
Figures 4.18 and 4.19 show the material removal rate results of welded seams for an ‘as received’ condition tool and a tool with 25 minutes of continuous use, receptively. In Figure 4.16 we can appreciate a approximate steady straight line for both ‘new’ and 25 minute old tools. This is the expected result for such data, as the tool carves material at a very steady pace. Notice the material removal rate for the ‘new’ tool is slightly higher than for the 25 minute old tool, this is also expected due to the tool wear and aging.

In Figure 4.17, material removal rate for AH-36 steel shows a different trend than the one for ABS-A steel. For the ‘new’ tool the material removal rate has a decaying slope, unlike in the ABS-A steady rate line, which shows the significant wear and tear the tool experiences while working on AH-36 steel reported previously. The 25 minute old tool material removal rate has the expected steady straight line. This flat line, for the 25 minute tool, however the gap between the new and 25 minute tool lines is much bigger than the one for ABS-A steel. This is an indication once again that the bristle blasting process does not perform well on steel AH-36 after a few minutes of continuous use of the tool.

Figures 4.18 and 4.19 compare the performance of the ‘new’ and a 25 minute old tool respectively, on steels ABS-A and AH-36. The ‘new’ tool (Figure 4.18) material removal rate shows how different the tool behaves while working on ABS-A or AH-36. The ABS-A steel data shows a constant material removal rate over an approximate 90 second time period. While the AH-36 steel data shows signs of decay and significant
changes in performance of the tool as the material removal rate slopes down. Figure 4.19 shows a similar trend of the tool’s performance, however, the results show a slight better performance of the tool on ABS-A steel.

4.3. Surface Texture Studies on Welded Joints

4.3.1. Introduction to Surface Texture Studies on Welded Joints

As previously outlined in Section 3.3, the surface texture and surface profile that the bristle blasting process produces is an extremely important characteristic and metric to assess the proficiency of the process on a specific material, including welded seams. Weld seams are common in the design and construction of commercial ships and are a critical component of the vessels structural integrity. Thus, they must be kept corrosion free and the proper surface texture must be achieved, to ensure a successful adhesion of any protective coatings that are applied to them.

4.3.2. Experimental Set-Up and Procedure for Surface Texture Studies on Welded Seams

For the surface texture studies the crown of the weld joint provides an adequate region for assessing the actual profile that is imparted to the weld seam by the bristle blasting tool. Therefore, a select number of weld crowns on specimens were cleaned manually, and the surface profile was measured using the Mitutoyo Surftest SJ 301 stylus type surface roughness measurement instrument. Two different tools were used for the
texture surface studies, a ‘new’ (as-received) tool and a tool that had acquire 25 minutes of service. A total of four specimens were used in the experiment, two ABS-A and two AH-36 and a single cleaning pass was conducted on each with an specific tool. Three surface roughness measurement were taken with the Mitutoyo Surftest SJ 301 and the collected $R_z$ number was averaged.

**4.3.3. Results for the Surface Texture Studies on Welded Seams**

Typical profiles of the cleaned weld crowns that were generated using an as-received bristle blasting tool (single pass) are shown in Figures 4.20 and 4.21 for both ABS-A (Fig 4.20) and AH-36 (Fig. 4.21). Figures 4.22 and 4.23 show the generated profile using a 25 minute old tool for bot ABS-A (Fig. 4.22) and AH-36 (Fig. 4.23). In each case, the contact region is narrow and indicates that the prepared surface has been generated by single (primary) impact between the bristle tips and weld bead surface. Also, remnants of the (solidified) weld flow lines still remain visible after the surface treatment, which is characteristic of the uniform, non-selective, and gradual material removal performance of the bristle blasting process. The raw data collected with the Mitutoyo Surftest SJ 301 can be found in the Appendix (Figures A.3 - A.6). Figure 4.24 shows the tabulated results for surface texture parameter $R_z$ for both ABS-A and AH-36 steel using both as-received tools and service accrued (25 min.) tools. The results obtained from these texture studies will be discussed in the next section.
4.3.4. Discussion of Results for Surface Texture Studies on Welded Seams

The welded specimens used for the surface texture study on welded seams can be viewed in Figures 4.20 through 4.23. As mentioned before, the single pass of the bristle blasting tool is clearly seen on the weld crown, which is where the surface texture measurements were taken. The collected surface roughness data is shown in Figure 4.24, where surface texture parameter $R_z$ is shown for ABS-A and AH-36 steel using both as-received tools and service accrued (25 min.) tools. In each case the results exhibit similar trends, and indicate that the mean profile $R_z$ of 90µm is routinely obtained for as-received tools, whereas the mean profile generated by tools that have acquired nearly 1/2 hr. of service corresponds to $R_z$ of 50µm. It is important to note that the $R_z$ values for the AH-36 are slightly lower than for the ABS-A, however the bristle blasting process performs with optimal results on both materials welded seams. This condition could be due to the fact that the weld bead hardness is lower than the AH-36 parent material hardness, a conditioned described in section 4.1.1. Thus being easier for the bristle blasting tool to create a rough surface profile that resembles the ABS-A one, but slightly inferior due to the fact that the tool was aged on AH-36 steel.

4.4. Cleanliness Study of Welded Seams

4.4.1. Introduction to Cleanliness Study of Welded Seams

Section 3.4 explains that aside from the quantitative experiments, such as the material removal studies and surface texture studies, the surface cleanliness is one of the
main objectives of the tool. The ability to remove corrosive material and achieve a certain surface cleanliness standard i.e., SP-11, SP-10, SP-5, etc. Unfortunately these surface cleanliness standards merely catalog the visual appearance/cleanliness and that one may expect to achieve when specific tools and/or apparatus are properly used for cleaning applications. The actual cleanliness results that are achieved ultimately depend upon the knowledge, experience, and skill of those performing the task. Consequently, trained users must have a basic understanding of the physical principles that underlie the tools and processes that are being used for surface treatment applications.

It is well known for example, that all surface preparation tools and processes have functional requirements that must be understood in order to successfully adapt the tool for removing surface contaminants and exposing unblemished base metal. If, for example, the free stream of grit blast media is masked or impaired from having direct contact with the target surface, cleaning cannot be achieved. Similar reasoning, of course, applies to all media and cleaning processes. In this section, emphasis is placed upon identifying the weld joint cleaning patterns that are inherent to the bristle blast process, whereas the degree and classification of cleanliness is left as a separate matter that is assessed by examining a specific weld cleaning application.

4.4.2. Experimental Set-Up and Procedure for Cleanliness Study of Welded Seams

To assess the performance of the patterns which the user can adopt, the bristle blasting cleaning study was divided into two different cases. The first case is when the
tool feed is parallel to the weld bead. The second case, is when the tool feed is perpendicular to the weld bead. A single pass of overlapping movement would be applied on both cases and with the customary implementation technique of the bristle blasting process shown in Figure 1.17. To conclude the cleaning study, a thorough cleaning of a weld bead located at the intersection of two plates oriented at 90 degrees is carried out.

4.4.3. Results for Cleanliness Study of Welded Seams

As mentioned before, the weld cleaning performance is case 1 is evaluated by examining the results that are obtained when the user is aligned perpendicular to the weld, and movement of the tool proceeds along the direction (i.e., parallel) to the weld bead. Hence, the cleaning results generated by this process technique are shown in Figure 4.25a. It is important to emphasize that the result shown in Figure 4.25a has been generated by single pass, overlapping movement of the tool along the direction of the weld bead and the joined plates.

The second case weld cleaning performance is evaluated by examining the results that are obtained when the user applies the tool across (i.e., perpendicular) the weld bead. In this case, the tool repeatedly traverses the weld bead, and complete coverage is achieved by sequentially overlapping each previously cleaned portion of the weld. This alternate method has been used to generate the surface shown in Figure 4.25b, and indicates that both the left and right seams of the weld toe have been fully exposed to the direct impact of bristle tips. That is, when used in this manner, the elevation of the weld
crown does not mask/impede contact with either side of the weld toe and, therefore, the overall cleanliness of the weld bead surpasses that shown in Figure 4.25a.

As mentioned previously a thorough weld bead cleaning was carried out. In the case a formidable application is chosen that illustrates the weld cleaning performance of bristle blasting that can be achieved when following the procedure previously outlined in the second case. Here, the weld bead is located at the intersection of two plates that are oriented at 90 degrees, which is generally regarded as an application wherein tool access/workspace restrictions are present. Initial condition of the weld bead surface is shown in Figures 4.26a and 4.26b (see inset), which depicts typical spatter and slag that is commonly generated during the formation of welded joints. The procedure that was used for cleaning this weld has been outlined above (see case 2); that is, the tool has been applied cross-wise (i.e., perpendicular) to the weld bead with each pass successively overlapping the previous path. Subsequently, the work part was inverted (i.e., the tool was reoriented 180 degrees), and the weld bead was again cleaned using previously described methods. The final cleanliness of the overall weld bead is shown in Figure 4.27a and further detail of the cleaned weld bead surface can be observed in Figure 4.27b.

4.4.4. Discussion of Results for Cleanliness Study of Welded Seams

Careful examination of Figure 4.25a, where the bristle blasting tool pass direction was parallel to the weld bead, indicates that as bristles strike the surface, wire tips directly impact the top of the toe weld, leading to complete cleaning along this part of the
weld seam. Similarly, the crown of the weld bead is both cleaned and textured. However, the bottom of the toe weld shows little or no evidence of bristle tip contact, because this portion of the contact zone is partially masked by the elevated (domed-shaped) weld crown. Nevertheless, it is evident that the lower portion of the weld seam can be cleaned by approaching the weld bead from the opposite direction; that is, a 180 degree reorientation of the tool will promote direct impact of bristle tips with this (lower)portion of the weld seam.

Examining Figure 4.25b, where the bristle blasting tool pass direction was perpendicular to the weld bead, does reveal trace locations (see circled regions) where incomplete cleaning has occurred due to local surface anomalies that partially shield the contact of bristle tips. Consequently, complete and thorough cleaning of the weld can be obtained by, once again, approaching the weld bead from the opposite direction; that is, a 180 degree reorientation of the tool will provide full cleaning coverage of the weld seam.

Comparing Figures 4.26 and 4.27 show the level of cleanliness that the bristle blasting process can achieve by using the tool perpendicular to the weld bead and sequentially rotate the tool 180 degrees and make another pass. A detailed cleanliness view of the weld bead, before and after, (see insets) is magnified and shown in Figures 4.26a and 4.27b, whereby both the weld crown and weld toe are observed to be completely free of corrosive slag. Thus proving that the bristle blasting process is very adequate for weld seam cleaning.
Figure 4.1: (a) Front weld bead and weld pool segment (inset), and (b) rear weld bead of ABS-A welded specimens (Ref. 26).

Figure 4.2: (a) Front weld bead and weld pool segment (inset), and (b) rear weld bead of AH-36 welded specimens (Ref. 26).
Figure 4.3: ABS-A weld specimen cross-section of metallographically prepared specimen illustrating top weld bead, base metal (parent material), and bottom weld bead (Ref. 26).

Figure 4.4: AH-36 weld specimen cross-section of metallographically prepared specimen illustrating top weld bead, base metal (parent material), and bottom weld bead (Ref. 26).
Figure 4.5: Vickers micro-hardness measurements of top (a) and bottom (b) weld beads fabricated on steel ABS-A (Ref. 26).
Figure 4.6: Vickers micro-hardness measurements of top (a) and bottom (b) weld beads fabricated on steel AH-36 (Ref. 26).
Figure 4.7: Initial condition of ABS-A plates joined at 90 degrees with a T-joint style weld.

Figure 4.8: Initial condition of Ah-36 plates joined at 90 degrees with a T-joint style weld.
Figure 4.9: Bristle blast surface of specimen used in material removal study for (a) ABS-A welded joint, and (b) AH-36 welded joint (Ref. 26).

Figure 4.10: Weld material removal (gram weight) versus duration of tool contact (seconds) for new tool and 25 minute duty cycle tool on steel ABS-A weld seam.
Figure 4.11: Weld material removal (gram weight) versus duration of tool contact (seconds) for new tool and 25 minute duty cycle tool on steel AH-36 weld seam.

Figure 4.12: Comparison of weld seam and base metal material removal performance using new tool on steel ABS-A welded specimen.
Figure 4.13: Comparison of weld seam and base metal material removal performance using new tool on steel AH-36 welded specimen.

Figure 4.14: Comparison of weld seam and base metal material removal performance for 25 minute duty cycle tool for steel ABS-A welded specimen.
Figure 4.15: Comparison of weld seam and base metal material removal performance for 25 minute duty cycle tool for steel AH-36 welded specimen.

Figure 4.16: Material removal rate (in gm/sec) versus time of contact of tool (in seconds) for 'new' and 25 minute old tool on steel weld seam of steel ABS-A specimen.
Figure 4.17: Material removal rate (in gm/sec) versus time of contact of tool (in seconds) for 'new' and 25 minute old tool on steel weld seam of steel AH-36 specimen.

Figure 4.18: Material removal rate caused by a 'new' (as-received) tool, comparison between weld seam specimens of steels ABS-A and AH-36.
Figure 4.19: Material removal rate caused by a 25 minute duty cycle tool, comparison between weld seam specimens of steels ABS-A and AH-36.

Figure 4.20: Single-pass profile generated along weld crown of ABS-A welded specimen with an as-received bristle blasting tool.
Figure 4.21: Single-pass profile generated along weld crown of AH-36 welded specimen with an as-received bristle blasting tool.

Figure 4.22: Single-pass profile generated along weld crown of ABS-A welded specimen with a 25 minute old bristle blasting tool.
Figure 4.23: Single-pass profile generated along weld crown of AH-36 welded specimen with a 25 minute old bristle blasting tool.

Figure 4.24: Measured surface roughness along weld crown using both new tools and 25 minute duty cycle tools on ABS-A and AH-36 weld beads.
Figure 4.25: Surface obtained by using single-pass of bristle blasting tool in direction (a) parallel to weld bead, and (b) perpendicular to weld bead (Ref. 26).

Figure 4.26: Initial condition of ABS-A plates joined at 90 degrees (a) overall view of weld bead and (b) inset view of weld pool segment (Ref. 26).
Figure 4.27: Weld bead cleaned via bristle blasting process for ABS-A plates joined at 90 degrees (a) overall view of cleaned weld bead and (b) inset view of cleaned weld pool segment (Ref. 26).
5. SUMMARY AND CONCLUSIONS FOR THE SURFACE PREPARATION OF NAVAL SHIP CONSTRUCTION STEELS (ABS-A AND AH-36) VIA BRISTLE BLASTING PROCESS

5.1. Overview of the Study and Conclusion

Throughout the duration of this study to assess the performance of the bristle blasting tool on Naval ship construction steels (ABS-A and AH-36), there were three main performance metrics investigated. These were Material Removal, Surface Texture and Cleanliness. In order to ensure success, the bristle blasting tool had to meet or exceed industry standards on each steel under investigation. In addition to the two different steels being investigated, weld seams were also included in the study due to the fact that they are important to the integrity of ship structures. To summarize the effectiveness and performance of the bristle blasting tool, the results each of for the performance indexes mentioned above will be stated separately for ABS-A, AH-36 and the welded seams.

5.1.1. Conclusion: Bristle Blasting Process for ABS-A Steel

The bristle blasting process is a viable and aggressive for removing corrosive layers while simultaneously generating an anchor profile on ABS-A steel. The corrosion removal capacity and surface cleanliness performance of the bristle blasting tool on this specific material system appears to be on par with the norms and standards that are commonly associated with grit blasting operations.
A direct comparison of bristle blasting tool performance with SSPC VIS 3 in conjunction with the power hand tool cleanliness standard SP 11 clearly indicates that the bristle blasting process surpasses the cleanliness and profile that is characteristic of all power tool cleaning processes, including hand tool cleaning by power brushes, sanding discs, and needle guns. Furthermore, comparison of the bristle blasting process with dry abrasive blast cleaning standard SSPC VIS 1 shows that performance of the bristle blasting process exceeds that of brush-off blast cleaning (SP 7), industrial blast cleaning (SP 14), and commercial blast cleaning (SP 6). Thoroughness of the bristle blasting process, however, appears to be on an equal par with near-white blast cleaning (SP 10) and white metal blast cleaning (SP 5). Thus, the disparity of the bristle blasting process with norms/standards cited in SP 11 suggests that a re-evaluation of this document is needed in order to accurately convey the performance of bristle blasting processes to the corrosion/surface finishing community.

5.1.2. Conclusion: Bristle Blasting Process for AH-36 Steel

The effectiveness of the bristle blasting process on AH-36 steel had some apparent shortcomings when compared with ABS-A steel. The material removal capability of the bristle blasting tool AH-36 steel shows the tool is capable of removing corrosive material and exposing substrate parent material. However, the tools material removal performance declines rapidly after 30 minutes of continuous use. This is an indication that AH-36 steel wears and dulls the bristle tips very quickly.
During the surface finish and tool life assessment studies on AH-36 steel, it became apparent that the bristle blasting tool exhibited a considerably shorter life span. The tool is able to create acceptable surface roughness texture (average $R_z$ of 57 microns) only during early stages of use. Happens, after 5 minutes of continuous use, the surface roughness texture drops to an average $R_z$ of 26 microns. This low $R_z$ level may be insufficient, as defined by industry standards, to have an acceptable texture for protective coatings. This lesser performance can, perhaps be traced to the 50% greater yield strength and 17% greater hardness then ABS-A steel.

5.1.3. Conclusion: Bristle Blasting Process for Welded Joint Seams

The second part of this study focused on the implementation of the bristle blasting process on welded seams. This is an important part of the investigation due to the fact that welded seams are present in the ships infrastructure. The welded seams present a geometric challenge because of their location and random shape. For this study production-quality welded joints were prepared from ABS-A and AH-36 steel, which is commonly used in the commercial ship building industry. Metallurgical and mechanical properties of the welded joints were examined and a series of experiments were carried out on welded specimens to help assess the material removal, profile/texture, and cleanliness performance of the bristle blasting process. Based upon the studies carried out the following conclusions can be reached.
During the metallurgical investigation, it was demonstrated that the hardness of the weld bead can vary by as much as 10-25% when compared with the parent (base metal) steels that are being joined. For example, the weld bead hardness for AH-36 steel is lower than the parent material, and the weld bead exhibited a dendritic pattern of ferritic grains with coarse and fine grain boundaries. This is also observed for the ABS-A steel.

The material removal experimental data correlated very well with the expectations. On the ABS-A weld bead samples, the material removal performance of the tool was approximately the same as on the ABS-A base metal. However, the AH-36 weld bead has a greater propensity for material removal than AH-36 base metal. The latter observation suggests that the weld bead material of AH-36 steel is preferentially abraded when compared to parent material during the surface preparation process. Furthermore, the material removal rate was derived from the material removal data (i.e. direct slope), and the graphs displayed the expected decaying shapes (with the exception of the 25 minute tool used on steel AH-36). As mentioned previously, the AH-36 material system has a significant impact on the tool life and performance characteristics. Nevertheless, the bristle blasting tool performs adequately, from a material removal perspective, on ABS-A steel. It also performs adequately on AH-36 steel until it reaches 25 minutes of continuous use.
The surface roughness and texture test, demonstrates that the average roughness profile of bristle blasted welds can vary from $R_z=90\ \mu m$ (as received tool) to $R_z=50\ \mu m$ (tool having 25 minutes of accrued service). This surface profile range is desired for the texture requirements of paints and protective coatings by the industry.

Lastly, two distinctly different methods were shown to be viable for weld cleaning, namely, parallel and perpendicular tool movement relative to the weld seam. In general, complete and thorough cleaning of the weld is obtained by approaching the weld bead from two different (i.e., mutually opposite) directions. Nevertheless, the use of perpendicular (i.e., crosswise) tool movement relative to the weld bead can lead to improved cleaning along the toe weld when compared with parallel tool movement relative to the weld bead; In addition, crosswise movement of the tool may produce near-white metal cleanliness (i.e., SP-10) without the need for reworking the weld bead in the opposite direction. White metal cleanliness (i.e., SP-5) can be achieved along standard flat welds (i.e., butt joint) surfaces as well as along the intersection of two plates that are oriented at 90 degrees. These successful cleaning methods worked on both ABS-A and AH-36 welded samples.
## APPENDIX

Table A.1: Approximate Material Removal Rates for Steels ABS-A and AH-36

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Table A.2: Vickers Micro-Hardness (500g load) Data Collected for Steel ABS-A

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Total Average | 155.8 |
Table A.3: Vickers Micro-Hardness (500g load) Data Collected for Steel AH-36

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| Total Average  | 182.8          |
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Figure A.1: Material chemical composition for steel ABS-B. Courtesy of Chapel Steels.
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1700 HOLT RD N.E.
Tuscaloosa, AL 35404-1000
800-837-8372

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**Grade:**

**Order Description:**

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**Quality Plan Description:**

ABS DH36/MLS/50: ABS AN/OS/MLS-2298C DH36/A572-50/A709-50 -22F

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**Customer:**

Sold TO:
CHAPEL STEEL CO. Houston TX

Ship TO:
Chapel Steel Co. Spring House PA

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**Figure A.2:** Material chemical composition for steel AH-36. Courtesy of Chapel Steels.
Figure A.3: Mitutoyo Surftest SJ 301 surface profile results strips for ABS-A welded sample profile produced by an 'as-received' bristle blasting tool.
Figure A.4: Mitutoyo Surftest SJ 301 surface profile results strips for ABS-A welded sample profile produced by a 25 minute old bristle blasting tool.
Figure A.5: Mitutoyo Surftest SJ 301 surface profile results strips for AH-36 welded sample profile produced by an 'as-received' bristle blasting tool.
Figure A.6: Mitutoyo Surftest SJ 301 surface profile results strips for AH-36 welded sample profile produced by a 25 minute old bristle blasting tool.
BIBLIOGRAPHY


23. SSPC-VIS 1, “Guide and Reference Photographs for Steel Surfaces Prepared by Dry Abrasive Blast Cleaning”. *Steel Structures Painting Council*, Publication No.02-12, Pittsburgh, PA 15213-3724


25. SSPC-VIS 1, “Guide and Reference Photographs for Steel Surfaces Prepared by Dry Abrasive Blast Cleaning”.